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Assessing Potential Health Effects from Municipal Sludge Incinerators

L. Fradkin, R. J. F. Bruins, S. D. Lutkenhoff, and J. F. Stara
Office of Research and Development
U.S. Environmental Protection Agency
Cincinnati, Ohio

E. Lomnitz and A. Rubin
Office of Water Regulations and Standards
U.S. Environmental Protection Agency
Washington, D.C.

This paper describes a risk assessment methodology for preliminary assessment of municipal sludge incineration. The methodology is a valuable tool in that it can be used for determining the hazard indices of chemical contaminants that might be present in sewage sludge used in incineration. The paper examines source characteristics (i.e., facility design), atmospheric dispersion of emission, and resulting human exposure and risk from sludge incinerators. Seven of the ten organics were screened for further investigation. An example of the calculations are presented for cadmium.

Risk assessment can be used to determine the likelihood that an environmental agent may cause human disease and the magnitude of the likely impact on public health. The methodology described here uses the principles of risk assessment to estimate the potential health impacts of incinerating sewage sludge. It has been developed to enable the rapid screening of a list of sludge contaminants by making a preliminary determination of which contaminants could potentially be emitted in amounts high enough to cause adverse effects. Because the goal is to develop a preliminary screening tool, the methodology used has been kept as simple as possible. Procedures for estimating potential exposures tend to be complex, and often require the use of simplifying assumptions. Modifying the assumptions used may cause the results to vary substantially. Therefore, assumptions used here tend to be conservative to prevent falsely negative determinations of hazard. However, to preserve the utility of the method, an effort has been made to ensure that the conservative assumptions are nevertheless realistic, or have a reasonable probability of occurring under unregulated or uncontrolled conditions.

Incineration is currently used on approximately 25 percent of the nation's wastewater sludge.[1] There are approximately 200 municipal sludge incinerators presently in operation in the United States.[1] Incinerator types most commonly used in the U.S. are the multiple hearth (approximately 80 percent) and fluidized bed (approximately 15 percent) designs. The multiple hearth incinerator is a staged process consisting of 4–12 hearths positioned one on top of the other. Sludge drying occurs in the upper hearths, combustion occurs in the central hearth, and ash cooling occurs in the lower hearths. An afterburner may be used at the exit of the furnace to reduce hydrocarbon emissions and eliminate odors. The fluidized bed incinerator has a single combustion chamber where combustion air flows upward through a suspended sand bed creating a turbulent combustion zone. Sludge drying and combustion occur simultaneously in this incinerator. The combustion products, including the ash, exit through the top of the incinerator.

Although these two incinerator types are quite different in design, many of the system operating parameters are similar. The combustion temperature is typically between 1400 and 1700°F (760–927°C) and air pollution control equipment generally consists of a high efficiency venturi scrubber followed by a tray-type wet scrubber.

The sidestreams generated from this disposal technology differ somewhat between combustion systems. The multiple hearth furnace produces bottom ash, demister effluent, and a wet scrubber slurry which yields a fly ash and scrubber water. The fluidized bed incinerator has no bottom ash; all of the solids exit the combustion zone through the top of the furnace.

The multiple hearth sludge incinerator was chosen for this analysis because of the greater number of publicly-owned treatment works (POTW) that utilize this technology and the relative availability of data. The components of the analysis discussed in this paper are sludge contaminant concentration, source characteristics, emission rate estimates, dispersion parameters and health risk values. A hazard index is a ratio that is used to reduce a large and complex body of data to terms that facilitate evaluation and decision-making. The U.S. Environmental Protection Agency is utilizing the hazard indices to prioritize chemicals for further analysis. An example for cadmium is presented as well as the results of this screening exercise.

Sludge Contaminant Concentration

Sludge contaminant levels may be viewed as the starting point for this method. A valid estimate of the level of contamination is essential to determine if a hazard exists. Without it, none of the hazard indices for a given

Table I. Relationship between loss of metals in emissions relative to metals in feed and the loss in total emissions relative to total ash content of feed for five multiple hearth furnace/wet scrubber systems.

Metal	Loss of	Multiple hearth furnace/wet scrubber systems Percentage of metal and ash lost in system[a] (1)	(2)	(3)	(4)	(5)
Cd	Metal[b]	5.5	11	28	37	42
	Ash[c]	0.019	0.12	0.16	0.13	0.29
Cr	Metal	0.035	0.26	0.27	0.43	0.92
	Ash	0.019	0.16	0.12	0.13	0.29
Cu	Metal	0.048	0.25	0.64	0.64	2.2
	Ash	0.019	0.12	0.16	0.13	0.29
Ni	Metal	0.012	0.14	0.15	0.39	0.97
	Ash	0.019	0.13	0.12	0.16	0.29
Pb	Metal	3.6	3.8	3.8	5.7	32
	Ash	0.13	0.019	0.16	0.12	0.29
Zn	Metal	0.24	0.29	0.71	1.6	11
	Ash	0.12	0.019	0.16	0.13	0.29

[a] For each metal, losses are ranked, increasing from left to right. The third column of numerals is the median value.
[b] Metal loss = (metal emission rate + metal feed rate) × 100.
[c] Ash loss = (total emissions rate + total feed rate of nonvolatiles) × 100.

municipal incinerator can be calculated. Sludge concentrations tend to be log-normally distributed; that is, for a given chemical, the majority of POTWs have comparatively low sludge concentration levels and a few have much higher concentrations. Because of the importance of chemical contaminant concentrations in sludge for each of the indices, typical and worst-case values are chosen for this parameter. For most contaminants, data on sludge concentrations were derived from a U.S. EPA survey which investigated the fate and transport of priority pollutants from POTWs of 40 U.S. cities.[2] Where the latter study lacked data on a specific pollutant of concern, other literature sources were used. Where possible, median and 95th percentile concentrations were used to represent the typical and worst cases, respectively.

Source Characteristics

Source characteristics included in this methodology are exit gas temperature, exit gas velocity, stack height and stack diameter. The operating assumptions for this analysis were based on typical operations. The combustion zone temperature is assumed to be 1400°F (760°C) with the gases at the furnace exit ranging between 700°F and 1000°F (371–538°C).

Table II. Estimates of average case and reasonable worst case percentage losses of metals for multiple hearth furnaces/wet scrubber systems.

Metal	Average percent loss (%)	Reasonable worst case[a] (%)
Cd	30	40
Cr	0.3	0.6
Cu	0.7	0.9
Ni	0.2	0.6
Pb	4.0	10
Zn	0.8	4

[a] 95th percentile values.

A feed rate of 2660 kg per hour of sludge (dry weight basis) was chosen for the typical case. This rate would serve a community of approximately 400,000 people. For the worst case, a feed rate of 10,000 kg/h was chosen to represent several multiple hearth incinerators functioning in a single facility. The combustion air is equal to 100 percent excess air overall. The flue gas is cooled to 105°F (41°C) to reduce the plume's moisture content.

Emission Rate Estimates

The emission factors used in this work were based on an analysis of emission data from a U.S. EPA study of sludge incinerators in ten U.S. cities.[3] Five of the incinerators yielded data amenable to estimation of emission rates.

Emission losses for six metals are shown in Table I. Percentage metal losses increase from left to right in Table I. Corresponding ash losses are recorded for each metal loss. Examination of the results in the table shows that ash loss also tends to increase from left to right, indicating a correlation between ash loss and metal loss.

Based on the results of Table I, estimates of average-case and reasonable worst-case percentage losses of metals for multiple hearth furnaces/wet scrubbers systems are presented in Table II. These estimates assume that the wet scrubber controls emissions to values at or below the EPA standard of 0.65 g/kg of solid feed. Data for the remaining metals were from additional U.S. EPA surveys. For organics, the data are extremely limited.

Dispersion Parameters

Two types of input are necessary to describe this dispersion process—plume characteristics and meteorological data. Depending on the degree of sophistication, a variety of modeling parameters may be used to describe the behavior of the plume. Some of the more common parameters include: plume rise (i.e. final or gradual), buoyance-induced dispersion, stack tip downwash, building wake effects, rural/urban mixing heights and dispersion coefficients. The Industrial Source Complex Long Term (ISCLT) model, a widely used dispersion model developed by EPA, was used to estimate atmospheric chemical concentrations that would result from a hypothetical multiple hearth sludge incinerator under typical and worst case scenarios. The maximum concentrations generated by the ISCLT Model for this analysis, using an emission rate of 1 g/s, were 3.4 $\mu g/m^3$ for the typical scenario and

Table III. Source data for typical and worst case scenarios.

Source parameters	Scenarios Typical case	Worst case
Emission rate (g/s)	1.0	1.0
Stack exit velocity (m/s)	20.0	10.0
Stack diameter (m)	0.6	0.8
Stack exit temperature (K)	356.9	313.8
Stack height (m)	20.0	10.0
Building height (m)	16.5	8.25
Building width (m)	30.5	30.5
Building length (m)	45.73	45.73

16.0 $\mu g/m^3$ for the reasonable worst case scenario. Since concentrations are linearly related to emission rates, maximum concentrations for emission rates other than 1 g/s can be found by multiplying these concentrations by the appropriate emission rate. The source data for each scenario are presented in Table III. The building dimensions used for the typical scenario were those of a municipal incinerator located in Hampton, Virginia. For the worst case scenario the stack height was reduced from 20 to 10 meters and the building height was reduced from 16.5 to 8.25 m.

The principal meteorological input to the ISCLT Model is a tabulation of the joint frequency of occurrence of wind-speed and wind direction categories, classified according to the Pasquill stability categories. Ideally, 70 years of meteorological data are needed to generate lifetime exposure concentrations. However, in practice only five years of meteorological data are routinely input to the ISCLT Model to obtain lifetime exposure concentrations. For this modeling analysis, five consecutive years (1965–1969) of 3-hourly wind and stability data from the Houston, Texas, National Weather Service station was used. Since this is a hypothetical sludge incinerator, the choice of Houston, Texas, meteorology was arbitrary. Past experience indicates that if other meteorology sites were used, concentration estimates would not change by more than a factor of two.

For the ISCLT modeling analysis, the receptor grid consisted of 13 downwind distances located along 16 radials. The radials were separated by 22.5 degree intervals beginning with 0 degrees and proceeding clockwise to 337.5 degrees. The 13 downwind distances for each radial were: 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 1.0, 1.2, 1.5, 2.0 and 5.0 km.

The ISCLT Model also requires the input of ambient temperatures and mixing heights by stability category. There are six stability categories—A through F where Class A is the most stable, Class D is the neutral class used for overcast conditions during the day or night, and Class F is the least stable. The average annual maximum daily temperature for Houston, Texas, was assigned to the A, B and C stability categories; the average mean daily temperature was assigned to the D stability category and average annual minimum daily temperature was assigned to the E and F stability categories. Urban mixing heights and stability categories were used for this analysis, since sludge incinerators are usually located in urban areas. The Holzworth mean afternoon mixing height for Houston, Texas, was assigned to the B and C stability categories; 1.5 times the mean afternoon mixing height was assigned to the A stability category; the mean early morning and afternoon mixing heights were assigned to the D stability category.

Calculation of Hazard Indices

Two types of hazard indices are derived, one type showing the expected increase of contaminant concentration in an environmental medium ("incremental index") and the other showing whether adverse effects could result ("effect index"). Careful interpretation of these indices indicates whether a more detailed analysis of a chemical should be undertaken or whether the chemical can be screened out at this stage.

The incremental index (I_i) shows the expected degree of increase of contaminant concentration in air from municipal sludge incineration. The incremental index does not by itself indicate hazard, since contamination alone does not necessarily mean that adverse effects in humans will occur. However, the incremental index aids in both the calculation and interpretation of the subsequent effect indices. The calculation method for an index of air concentration increment resulting from incinerator emissions is the following:

$$I_i = \frac{(C \times DS \times SC \times FM \times DP) + BA}{BA} \quad (1)$$

where: C = coefficient to correct for mass and time units (h/s × g/mg)
DS = sludge feed rate (kg/h dry weight)
SC = sludge concentration of pollutant (mg/kg dry weight)
FM = fraction of pollutant emitted through stack (unitless)
DP = dispersion parameter for estimating maximum annual ground level concentration ($\mu g/m^3 \cdot g/s^{-1}$), and
BA = background concentration of pollutant in urban air ($\mu g/m^3$).

Effect indices (I_e) show whether a given increase in contaminant level could be expected to result in a given adverse impact on health of humans. The calculation method for an effect index of human health risk resulting from inhalation of incinerator emission is the following:

$$I_e = \frac{I_i \times BA}{EC} \quad (2)$$

where: I_i = incremental index = index of air concentration increment resulting from incinerator emissions (unitless)
BA = background concentration of pollutant in urban air ($\mu g/m^3$), and
EC = exposure criterion ($\mu g/m^3$).

The interpretation of I_e varies according to whether the exposure criterion (EC) refers to a threshold or nonthreshold effect. Threshold effects are those for which a safe level of contaminant exposure can be defined. The U.S. EPA considers all noncarcinogenic effects to have thresholds. The value chosen for EC is usually based on an established reference dose (RfD), which usually is designed to be below the threshold for chronic toxicity. Therefore, if $I_e < 1$ the adverse effect is considered unlikely to occur, whereas if $I_e > 1$ the effect cannot be ruled out. Values of I_e close to 1 may be somewhat ambiguous and require careful interpretation.

The U.S. EPA considers carcinogenic effects to be nonthreshold; that is, any level of exposure to a carcinogenic contaminant is regarded as posing some risk. Since no threshold can be identified, a benchmark level of risk was chosen against which to evaluate carcinogen exposures. The Carcinogen Assessment Group of the U.S. EPA has estimated the carcinogenic potency (i.e. the slope of risk versus exposure) for humans exposed to low dose levels of carcinogens. These potency values indicate the upper 95 percent confidence limit estimate of excess cancer risk for individuals experiencing a given exposure over a 70-year lifetime. They can also be used to derive the exposure level expected to correspond to a given level of excess risk. A risk level of 10^{-6}, or one in one million, was chosen as an arbitrary benchmark in defining the exposure criterion (EC) for carcinogens. Therefore, for nonthreshold effects, if $I_e > 1$ then the cancer risk resulting from the sludge incinerator may exceed 10^{-6}. Effect indices based on nonthreshold effects must be clearly differentiated from those based on threshold effects, since their interpretation is fundamentally different. Subthreshold exposures are normally considered acceptable, whereas the acceptability of a given low level of risk is less clear.

Other assumptions about human exposure were also required in order to define EC. A most-exposed individual (MEI), rather than a typical individual, was defined as a basis for this analysis since a conservative outcome was desired and because definition of the "ty-

Table IV. Assumptions of the U.S. EPA Industrial Source Complex Long Term (ISCLT) Model.

Source characteristics	Input data "Typical case"	"Worst case"
Combustion zone temperature	1400°F	1400°F
Solids content	28%	26%
Stack height	20 m	10 m
Exit gas velocity	20 m/s	10 m/s
Exit gas temperature	356.9 K (183°F)	313.8 K (105°F)
Stack diameter	0.60 m	0.80 m

pical" individual entails a more complete characterization of the whole exposed population. The MEI was assumed to reside in the area of maximum annual ground level concentration and to be exposed 24 hours a day. The incinerator was assumed to be operational for the life of the individual (70 years) and to be operational 100 percent of the time. The 70-year exposure was considered valid since POTWs are expected to be operated indefinitely into the future.

An inhalation volume of 20 m^3 of air inspired on a daily basis was assumed, which is consistent with other U.S. EPA analyses. For this analysis it was assumed that 100 percent of the inhaled particulate enters and is retained in the upper and lower respiratory tract.

Example Calculations for Cadmium

The incremental index (I_i) utilizes the following data input for the incineration of cadmium (Cd):

- *Coefficient (C) to correct for mass and time units*: 2.78×10^{-7} h/s × g/mg
- *Sludge feed rate (DS)*: A feed rate of 2660 kg/h dry weight (DW) represents an average dewatered sludge feed rate into the furnace. This feed rate would serve a community of approximately 400,000 people. A higher feed rate of 10,000 kg/h DW would serve a major U.S. city. Each rate was incorporated into the U.S. EPA ISCLT model together with the input data listed in Table IV.
- *Sludge concentration of pollutant (SC)*: The typical (median) sludge concentration for Cd is 8.15 mg/kg DW and the reasonable worst case (95th percentile) is 88.13 mg/kg DW.[2]
- *Fraction of pollutant emitted through stack (FM)*: Emission estimates for Cd are from Table II; 30 percent for typical and 40 percent for reasonable worst case situations.
- *Dispersion parameter for estimating maximum ground level concentration (DP)*: The dispersion parameter is derived from the U.S. EPA ISCLT model; 3.4 $\mu g/m^3$ for typical and 16.0 $\mu g/m^3$ for worst case.
- *Background concentration of pollutant in urban air (BA)*: The median background concentration for Cd in urban air is less than 6×10^{-3} $\mu g/m^3$, which is the detection limit for Cd. Therefore, the background concentration selected was conservatively taken to be one-half of the detection limit.[4]

Therefore, the example calculation (using Equation 1) for the incremental index (I_i) of air concentration increment can be carried out as follows:

$$3.049 = [(2.78 \times 10^{-7}\ \text{h/s} \times \text{g/mg}) \times (2660\ \text{kg/h DW})(8.15\ \text{mg/kg DW}) \times (0.30)(3.4\ \mu g/m^3) + (3 \times 10^{-3}\ \mu g/m^3)] + 3 \times 10^{-3}\ \mu g/m^3 \quad (3)$$

The concentrations of Cd in air in this typical case calculation show that Cd is expected to substantially increase above the background concentration when sludge is incinerated.

Effect Index (I_e) of Human Cancer Risk Resulting from Inhalation of Incinerator Emission

- *Cancer potency*: The cancer potency of 6.1 $(mg/kg/day)^{-1}$ is estimated for inhalation of Cd by U.S. EPA.[5]
- *Exposure criterion (EC)*: The exposure criterion is calculated using the following formula:

$$EC = \frac{10^{-6} \times 10^3\ \mu g/mg \times 70\ kg}{6.1\ (mg/kg/day)^{-1} \times 20 m^3/day} = 5.7 \times 10^{-4}\ \mu g/m^3 \quad (4)$$

Table V. Index of air concentration increment (I_i) resulting from incinerator emissions.

Fraction of pollutant emitted through stack	Sludge concentrations	Incremental index at sludge feed rates (kg/h DW) 0	2660	10,000
Typical	Typical	1.0	3.0	37
	Worst	1.0	23	393
Worst case	Typical	1.0	3.7	49
	Worst	1.0	31	520

where: weight of average adult male = 70 kg
volume of inhaled air/day = 20 m^3/day
U.S. EPA Cancer Potency = 6.1 $mg/kg/day^{-1}$
one in a million exposed population = 10^{-6}
unit conversion factor = 10^3 $\mu g/mg$

The effect index (I_e) of human cancer risk resulting from inhalation of incinerator emission of cadmium (Cd) is as follows (using Equation 2):

$$I_e = \frac{(3.049)(3 \times 10^{-3}\ \mu g/m^3)}{5.7 \times 10^{-4}\ \mu g/m^3} = 15.8 \quad (5)$$

Equation 5 shows that the increased air concentrations of Cd resulting from sludge incineration are expected to

Table VI. Effect index of human cancer risk (I_e) resulting from inhalation of incinerator emission of cadmium.

Fraction of pollutant emitted through stack	Sludge concentrations	Effect index at sludge feed rates (kg/h DW) 0	2660	10,000
Typical	Typical	5.3	16	200
	Worst	5.3	120	2100
Worst case	Typical	5.3	20	260
	Worst	5.3	160	2800

Table VII. Results of the screening incineration health methodology.

Chemical	Effect indices[a] $I_e > 1$	$I_e < 1$
Arsenic[b]	X	
Beryllium[b]	X	
Cadmium[b]	X	
Chromium[b]	X	
Copper		X
Lead	X	
Mercury[c]	X	
Nickel[b]	X	
Selenium		X
Zinc		X

[a] Results are those for worst-case scenarios.
[b] Exposure criteria based on carcinogenic effects.
[c] The $I_e > 1$ for this chemical was due to the high background concentration rather than due to the contribution of sludge.

substantially increase the human cancer risk due to inhalation of Cd above the risk posed by background urban air concentrations of Cd.

The results for all I_i for typical and worst case scenarios for Cd are presented in Table V. The results for all I_e for typical and worst case scenarios for Cd are presented in Table VI. This screening methodology was used for a list of 10 chemicals. Seven chemicals had a hazard (effect) index $I_e > 1$ (Table VII).

Conclusions

This methodology for preliminary assessment of municipal sludge incineration is a valuable tool in that it can be used for determining the hazard indices of chemical contaminants that might be present in sewage sludge used in incineration. Although the hazard indices are intended for rapid and simplified decision-making (i.e., screening), they cannot be interpreted blindly. Their interpretation requires a familiarity with the fundamental principles underlying the generation and selection of the data on which they are based, and utilizing careful judgment on a case-by-case basis. The simplicity and conservatism that make this methodology useful for assessing potential risk and appropriate for screening of chemicals make it inappropriate for estimating regulatory criteria or standards.

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L. Fradkin, R. J. F. Bruins and S. D. Lutkenhoff are with the Environmental Criteria and Assessment Office, Office of Research and Development, U.S. Environmental Protection Agency, Cincinnati, OH 45268. A. Rubin is with the Wastewater Solids Criteria Branch, Office of Water Regulations and Standards, U.S. Environmental Protection Agency, Washington, DC 20360. This paper is dedicated to the late J. F. Stara and the late E. Lomnitz.

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